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Development and Verification of an IoT-enabled Air Quality Monitoring System Based on Petri Nets

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Abstract
An internet of things (IoT) system for monitoring environmental parameters on campus has been successfully developed in this study. Various sensors are adopted in front of the IoT system for detecting air pollutants. The architecture of LongRange in Class C uses low-power and long-distance transmission technologies, which has been set up on the large campus so that the terminal equipment can reach a balance between downlink latency and battery life, making it the best communication protocol. In addition, this monitoring system uses the Petri net software tool to build a correct IoT platform based on the fundamental design process and to demonstrate the feasibility of the IoT system through simulation-based verification. Finally, the experimental results indicate that the IoT system for monitoring the environmental parameters on campus achieves the goal of an acceptable data transmission success rate of more than 95%. Thus, it can facilitate the air quality trends for policy making as well as the hazardous prediction and prevention.

Keywords Long Range (LoRa) technology · Low power consumption network · Internet of things (IoT) · Environmental parameters monitoring · Smart campus

1 Introduction

Currently, morning exercise has become the energy source of people's daily life. Many people prefer to take jogging early in the morning. With regards to the air quality, the degree of pollution is increasing rapidly. In addition, due to climate change, the weather in every season of a year has varied significantly, especially, in summer and winter. According to the statistics of Central Weather Bureau in Taiwan, the average relative humidity reaches as high as 70% in summer [1]. With the influence of humidity, the actual temperature and the temperature felt by human body may be different even though the heat index and the wind chill index have been taken into consideration. Therefore, it motivates us to present this IoT system, in which the temperature and the air quality can be viewed as a basis to release reference standards, providing the outdoor air quality on

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campus to determine whether it is suitable for holding the outdoor activities or not [2, 3]. Furthermore, most campuses have many department and dormitory buildings, which usually occupy a large area.

Problem Statement: Since Ming Chi University of Technology (MCUT) has a tradition of morning jogging, students need to gather up and run around the sports field at 6:30 in the morning. Thus, the temperature and the air quality must be viewed as a reference standard, enabling teachers to determine whether the morning jogging is required or not. Many department buildings, faculty and student dormitories are distributed on campus. The air detection locations are set up in the 2nd Education Building and the 5th student dormitory to simultaneously monitor air pollutants, such as suspended particles (e.g. particulate matters, PM 2.5), carbon monoxide, and carbon dioxide, which are harmful to our health, reminding teachers and students to be always aware of the air pollutants. In the previous monitoring system, the problems such as low success rate of data transmission and high cost in system maintenance have ever been caused, which need to be solved now.

In this study, the LongRange (LoRa) communication technology was used to implement the IoT platform. By selecting the LoRaWAN in Class *C*, the data latency can be minimized [4]. Users can always pay more attention to whether the datasets are correctly collected. Thus, the terminal equipment can reach a balance between downlink latency and battery life. Various sensors are installed in different areas of the campus. The indoor data items include temperature, humidity, suspended particles (e. g. particulate matters, PM 2.5), carbon monoxide, and carbon dioxide, while the outdoor detection data items include temperature, humidity, wind speed, suspended particles, and ultraviolet light. In addition, the actual temperature is thus found out from the humidity and wind speed datasets collected.

Communication with the gateway was done through signal requirements to implement a low-power and long-range system. It is in line with class *C* for the LoRaWAN architecture, forming a two-way communication. In other words, through this type of instant messaging, the back end uses software applications such as *C#*, Azure, ASP.NET, and IIS to realize the construction of an air quality monitoring system on campus.

The gateway uses an industrial computer to write the *C#* Windows Forms application (App) to analyze the datasets from different detection stations and upload them to the Microsoft Azure cloud database system every hour, ensuring that the datasets are completely stored. The server uses ASP.NET to develop web programs to publish datasets and to integrate with the Google Map API for locating different detection stations. Users can search for the environmental quality and further carry out data analysis and evaluation through the website.

The remainder of this paper is organized as follows: The articles related to IoT platform with LoRa wireless transmission technology are discussed in Sect. 2. Section 3 focuses on the proposed hardware and software systems. The experimental results and performance evaluation are presented in Sect. 4. Finally, Sect. 5 remarks our conclusion.

2 Literature Review

This section first introduces the communication characteristics of IoT architecture. Then, the working principle of the wireless transmission technologies and Petri net definitions are presented.

2.1 LPWAN

Low-Power Wide-Area Network (LPWAN) [5, 6], also known as Low-Power Network (LPN), is a type of IoT architecture, which realizes a low-transmission and long-range wireless network. To achieve the design concept of low power consumption, the technology adopted by LPWAN is basically in the sub-GHz frequency band, thereby fulfilling the features required by LPWAN.

In other words, LPWAN has the characteristics of extremely low power consumption, long transmission range (usually *km* level), and low price [7]. However, it has the data load problem. In fact, LPWAN eliminates the shortcomings of the existing short-range cellular network technology. Shortening the transmission range means that the wide area network can be realized at lower cost while having better power consumption. These features can clearly explain the potential of LPWAN technology. The transmission range and power consumption of the current mainstream network for IoT, such as ZigBee, BlueTooth, Wi-Fi, RFID, 2G/3G/4G mobile networks, and so on, are not as good as those in the LPWAN architecture. Thus, the terminal devices of IoT do not usually require the transmission of a huge number of datasets.

LPWAN was developed after the establishment of IoT. Before the beginning of 2013, the term LPWAN did not exist. Currently, it has become one of the technologies that exhibit the fastest growth in the development of IoT. The IoT market demonstrates the incredible potential of LPWAN technology. Machina Research [6] predicted that there would be 3.6 billion LPWAN connections by 2024, which would grow substantially from today's number. The data transmission rate and transmission range of IoT technologies are divided into two categories, namely, one category in unauthorized frequency band such as LoRa, and the other category in authorized frequency band such as EC-GSM, LTE Cat-m, and NB-IoT.

The transmission range of ZigBee, BlueTooth, and Wi-Fi technologies is the shortest one in the unauthorized frequency band, while the transmission range of LoRa and UNB technologies is the longest one. Moreover, based on the power consumption and the data transmission rate [7], UNB technology exhibits the best power-saving performance, while LoRa technology shows low power consumption and moderate data transmission rate [8–11].

2.2 LoRa

LoRa is an emerging wireless technology designed specifically for LPWAN, providing long-range, low-speed, and low-power consumption wireless communication, which is considered as the most promising technology for realizing IoT applications. LoRa defines the physical layer communication lines. Many traditional communication systems use Frequency-Shift Keying (FSK) modulation as the physical layer, which can achieve low-power modulation. It is designed and patented by Semtech Corporation, which uses proprietary spread spectrum technology in the sub-GHZ ISM band. Bidirectional transmission uses Chirp Spread Spectrum (CSS), which is a sinusoidal signal of spread spectrum (SS) modulation that increases or decreases with time. LoRa allows six spreading spectrum factors (SF7 to SF12) and three different bandwidths (125 kHz, 250 kHz, 500 kHz). It is assumed that the higher spreading spectrum allows longer transmission range, but lower transmission speed (rate), and vice versa. The transmission rate of LoRa is from 300 bps to 50 kbps, and the maximum load length of each dataset is 243 bytes [12, 13].

LoRa-Alliance formulated the communication protocol and system architecture based on LoRa in 2015, which was named LoRaWAN™. According to the MAC layer protocol, power consumption level, LoRa® modulation and ISM bands in different regions around the world, this communication protocol and network architecture have a great impact on the node battery life, network capacity, service quality, and various application services. Based on the Open System Interconnection Reference Model (OSI), LoRa represents the physical layer, and LoRaWAN™ represents the data connection layer and the network layer [14, 15].

Many of the established network architectures still belong to the *mesh* network, in which each node can send messages to other nodes to increase the network communication range. However, it increases the operation complexity and shortens the battery life. In contrast, the *star* topology can realize long-range connection and make the battery more power-saving. The LoRaWAN™ architecture can be divided into end nodes, gateway, network server and application server. In terms of architecture, the end-devices are not connected to a specific gateway and the datasets are all received by multiple gateways. Gateway sends control signals and end-device messages to the cloud system, and simultaneously decodes multiple signals. The connection can be made through 3G, 4G or Ethernet, and the application server presents the results to all users [15].

Asynchronous communication data transmission protocol is used in the LoRaWAN™ architecture. This protocol is based on the Aloha system transmission method. In a mesh network or synchronous network, nodes must be woken up to synchronize with the network and to receive messages at any time. In such a mode, a lot of energy will be consumed, resulting in shortening the battery life. To achieve a long-range star topology, the gateway must have large capacity, which uses a multi-channel modulator-demodulator (MoDem) to receive messages of end-devices from all directions. However, the key factors include the transmission rate, the effective length of load datasets, and how long it takes to send the datasets. LoRaWAN™ is a spread-spectrum technology that uses different spreading spectrum factors, and the transmission rate changes accordingly [15].

There are three communication protocols defined for different services under the LoRaWAN™ standard. The terminal equipment achieves a balance between the downlink communication latency and the battery life, which is divided into Class *A*, Class *B*, and Class *C* [13–15]. Class *C* device allows bidirectional communication with maximal receiving slots. The receiving window is open at almost all the time and is only closed during transmission.

Class *A* terminal device is energy saving; however, its data transmission rate is low, which may easily delay. On the contrary, class *C* device has high power consumption. Since its receiving port is always open, it is in the best immediacy. Class *B* has the characteristics of signal synchronization. As a result, there is no need to continuously open the window for receiving signals like class *C*, and there is no problem in transmission efficiency like class *A*. Each type of device can be applied to different scenarios.

2.3 Petri Net

Petri net (*PN*) is a well-known graphical and mathematical model, which is characterized as concurrent, asynchronous, nondeterministic, stochastic, distributed, parallel, fuzzy, and so on. People use it to model and analyze various systems, different from flowcharts, block

Table 1 Formal PN mathematical definitions

Place (P)	$P = \{p_1, p_2, \ldots, p_n\}, n > 0$. A finite set of places
Transition (T)	$T = \{t_1, t_2, \ldots, t_m\}, m > 0$. A finite set of transitions
Flow (F)	$F \subseteq (P \times T) \cup (T \times P)$. A finite set of arcs (i.e. flow relation)
Weight (W)	$W: F \rightarrow \{1, 2, 3, \ldots\}$. Weight function
M_o	$M_0: P \rightarrow \{0, 1, 2, \ldots\}$. An initial marking

Table 2 PN Notations

Elements	Petri net symbols
Place(P)	○
Transition(T)	■ or □
Arc	→
Token	●

diagrams, and neural networks. The formal *PN* mathematical formula includes five elements, namely, $PN = (P, T, F, W, M_o)$. The formal *PN* mathematical definitions are listed in Tables 1 and 2. *PN* theory has been widely applied in the distributed and parallel systems. A *PN* model belongs to a directed graph including those elements such as place, transition, and the directed arc connecting places to transitions, and vice versa. A *PN* model owns parallel and concurrent modeling features, and it is also applied in the areas of system construction, property checking, systematic modularization, and so on [16, 17].

Workflow-Petri-net-Designer (WoPeD) is adopted as a software tool; and the *PN* model is used to modularize, simulate, and analyze the proposed approach and to help us get the experimental results [18]. WoPeD is an open-source software system developed by the Cooperative State University Karlsruhe under the GNU Lesser General Public License (LGPL), which serves as an easy-to-use system for simulating and analyzing the monitoring processes. In the WoPeD simulation, the analysis results are divided into two parts, namely, Wizard and Expert. Wizard part presents the workflow net property and the net statistics. Expert part presents the structural analysis and the soundness. Hence, the block diagram of the proposed monitoring system must be converted into a *PN* model for property analysis, which will verify its applicability and integrity.

2.4 Related Works

Wu [9] proposed an IoT scheme based on the Long Range (LoRa) modules on smart campus. The IoT scheme utilizes the low power modules and long-distance communication for monitoring temperature, humidity, and air quality with PM2.5 and CO_2. The design aims to obtain the maximum coverage using different spreading factors and bandwidths, which has been built at I-Sou University. However, it has unstable network connections with low success rate of data transmission. Lin [10] presented a campus air monitoring system with six detection locations using LoRa network. The datasets sent back to the cloud database system every minute through the Open Street Map (OSM) display allow one to immediately monitor the air quality at Tunghai University and the surrounding area. But its system maintenance is costly. Khanna and Kaur [11] proposed a comprehensive review article regarding IoT applications and challenges. The function of IoT is to unite every object of the world under one common infrastructure so that humans can not only control those objects; but also provide regular and timely updates on the current states. IoT concept was proposed a couple of years ago, but it may not be incorrect to quote that this term has become a benchmark for establishing communication among objects due to existing some big challenges.

3 Proposed Approach and Simulation Results

This section is divided into five parts to present the system architecture, hardware components, software architecture and tools, packet transmission specification, and system verification.

3.1 System Architecture

Figure 1 shows the proposed system architecture. Three detection stations were set up on campus. Different sensors were used and classified as indoor and outdoor ones, such as PMS5003T, MQ7, DS-CO2-20, GUVA-S12SD, and JL-FS2.

Indoor sensors are used to detect temperature, humidity, suspended particulates, carbon monoxide, carbon dioxide; while outdoor sensors are used to detect temperature, humidity, wind speed, apparent temperature, suspended particulates, and ultraviolet light, serving as an analysis basis. For data transmission, LoRa 915 MHz is used as the communication protocol, which is a transmission module LRM001 developed by Liyatech. The REVQ704 industrial computer developed by Avalue Technology is used as a Gateway. The C# Windows Forms program is installed to analyze the datasets collected from different detection stations. The datasets are uploaded to Microsoft Azure SQL Server every hour. Finally, the ASP.NET technology is adopted by the server to publish web pages which are integrated with the Google Map API to locate different detection stations, providing a graphical interface to users.

3.2 Hardware Components

The hardware components include Arduino Mega2560 Rev3 [19], XH-M401, PMS5003T [20], MQ-7 [21], GUVA-S12SD [22], JL-FS2 [23], DS-CO2-20 [24], LRM001 transceiver [25], RN2903 [26, 27], and Q7-REV07, which are divided into transmitter and receiver. The transmitter combines the corresponding sensors depending on the monitoring scenarios.

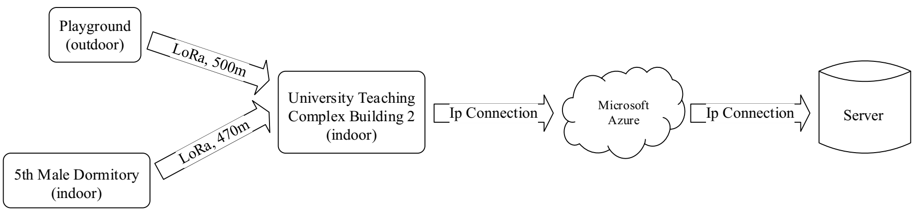

Fig. 1 System architecture

The indoor detection station is composed of the Arduino Mega2560 Rev3 development board and Liyatech LRM001 transceiver; and integrates the voltage stabilizing modules including PMS5003T, MQ7, DS-CO2-20, and XH-M401. The UART and ADC provided by Arduino are used as a communication channel to integrate the datasets of the above sensors, to define the packet specification hexadecimal string, and to transmit the UART protocol to the LRM001 transceiver module. The LoRa communication technology is utilized to upload the datasets to the receiver.

The outdoor detection station is also composed of the Arduino development board and LRM001; and integrates the voltage stabilizing modules including PMS5003T, GUVA-S12SD, JL-FS2, and XH-M401. The datasets are transmitted to LRM001 via UART and ADC, and the packet datasets are sent to the receiving end. The receiver is an industrial computer REVQ704, which is set as the system gateway. Since Arduino Mega2560 is connected to the sensors, it becomes one of the detection stations, which has a Mini PCI-E slot to connect the LRM001 and the UART communication at the same time, collecting all datasets into the installed C# Windows Forms program.

3.3 Software Architecture and Tools

The program of the corresponding environment is installed at the detection station, and the LoRa transmission mechanism is adopted to return it to the C# Windows Forms software application (App) [28]. Then all datasets are analyzed and published. The results can be obtained from the screen of the App to debug in the future. The results are uploaded to Microsoft Azure SQL Database and saved as a table with different settings. The effective datasets are then loaded using the Web Application of ASP.NET technology via the server [29]. In addition, the webpage is issued by IIS Service [30], enabling a connection to the server by using a physical network path, forming an interactive interface, and providing the public with complete data analysis results.

3.3.1 Internet Information Service

Internet Information Service (IIS) allows Microsoft system to provide the basic services for Internet users. It acts as a management platform for developing and managing web application services. This system includes the Windows Process Activation Service (WPAS), which enables the website to use protocols other than HTTP and HTTPS, and to integrate with the request management from IIS and ASP.NET. It includes the important functions of applications and web server in Windows Server 2008 (IIS7.0) and Windows Server 2008 R2 (IIS7.5). Therefore, IIS provides a graphical management interface to simplify the complexity in response to various management needs [30].

3.3.2 Microsoft Azure SQL Database

Cloud computing is a network-based method that can transfer hardware and software resources to servers, storage, database, and so on. It is established under the concept of virtualization, scalability, and Pay-As-You-Go. There are three cloud services, including infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS) [31].

Microsoft Azure is a public cloud service (PCS) platform launched by Microsoft. At first, it only provides basic cloud services with IaaS; and abundant services such as IaaS, PaaS, and SaaS are provided, allowing users to create services by using different methods. Azure categorizes the services into those groups including computing service, application service, data management, analysis service, network service, and so on, which are provided according to users' needs. This system uses Azure data management to build a database system in Azure SQL Database [32]. The gateway connects to the database system through the network and accesses the datasets in the database system, completing the cloud automation.

3.3.3 SQL Server Management Studio

SQL Server Management Studio (SSMS) is a graphical integrated environment that forms SQL infrastructure. It is applicable to SQL Server and Azure Database, providing the configuration and management of SQL Server. Users can quickly deploy, search, or upgrade the data layer used by Apps. Through either edge computer or cloud computer, users can perform the management by connecting to the database engine [33].

3.4 Packet Transmission Specification

The data transmission is customized according to a specific protocol. This system uses LoRa as the communication link. According to the RN2903 command manual, the packet transmission is defined by hexadecimal method. Arduino Mega 2560 integrates the sensor datasets with the command "radio tx", the detection station code, the data item abbreviation, and the detection value added in front of the datasets. After receiving the command, LRM001 sends it to the gateway for analysis.

3.5 System Verification

Figure 2 shows the block diagram of our proposed air quality monitoring system. Start the related hardware tools and make the sensors detect datasets. Send datasets to LRM001 transceiver for analysis. If the analysis results with desired values are passed, send datasets to App and store them in the SQL database system. Thus, the monitoring system is completed. The derived Petri net model is shown in Fig. 3. The interpretations of places and transitions are all listed in Tables 3 and 4, respectively. The place marking vector represents a current state in the monitoring system. The transition firing vector represents all processes that need to be changed under the current condition, and the arc represents a connection between place and transition.

For the net statistics shown in Fig. 4, there are 14 places, 18 transitions, and 36 arcs in total; and for the semantical analysis, there are no errors made in the Workflow net property with Soundness.

As shown in Fig. 3, p1 is like an input port and a token is inserted in *p1*. When Start system (*t1*) is completed, the token moves to Hardware (*p2*). Place *p2* enters the next step, namely, start hardware tools (*t2*); and transition *t2* fires to enter the gathering of sensor datasets (*p3*) when finished. If sensor datasets have problems, it returns to Hardware (*p2*) via Return and check hardware (*t3*). If there is no abnormality in the gathering of sensor datasets (*p3*), it moves to Sensor Datasets (*p4*) via Send (*t4*). LRM001 Client (*p5*) determines whether the datasets can be transmitted to the LRM001 Gateway (*p6*) via LoRa communication mechanism. If there is an error, the token returns to *p5* via Return and check LRM001 Client (*t8*); and the next LRM001 Gateway (*p6*) sends the datasets to C#

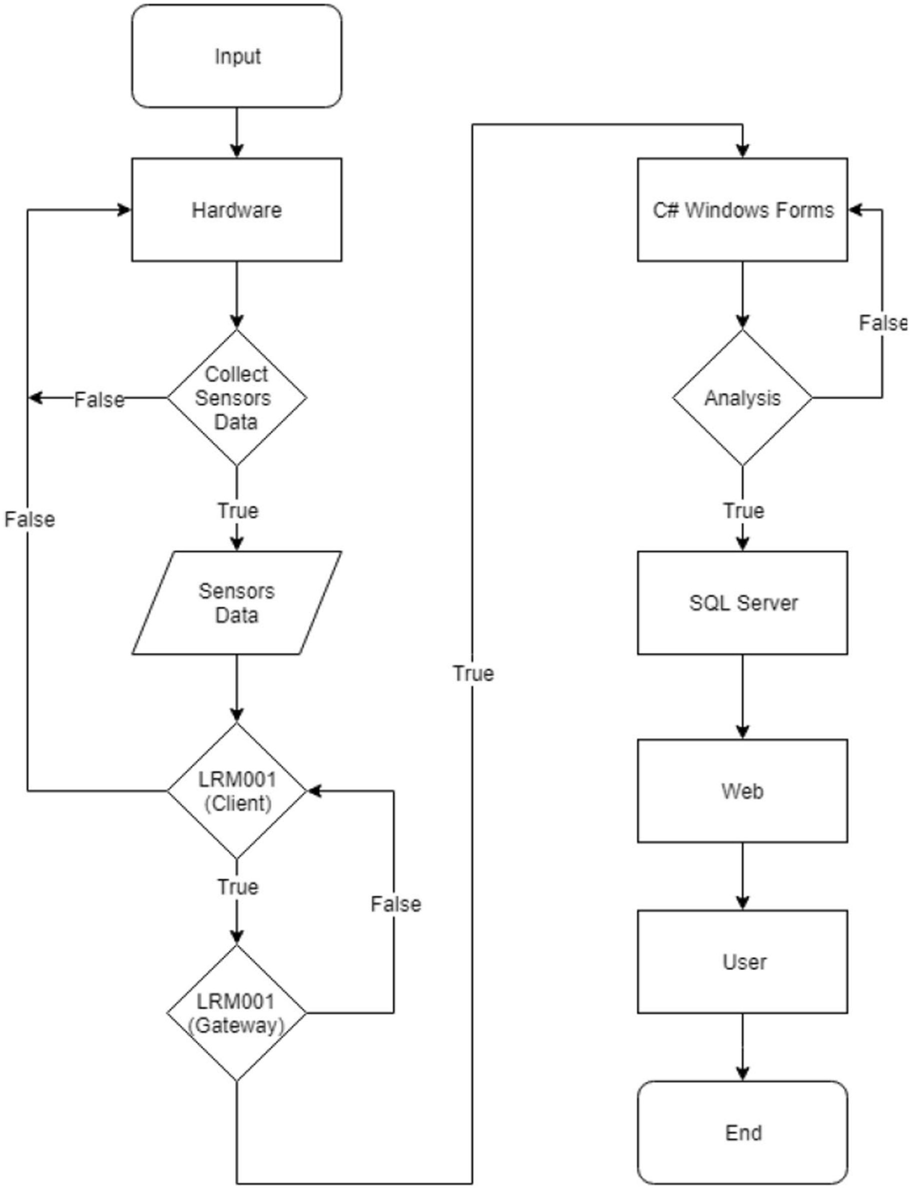

Fig. 2 Block diagram of the proposed monitoring system

Windows Forms (*p7*) and Analysis Data (*p8*), which are filtered into valid information and stored in Azure SQL Server (*p9*). ASP.NET Web Form (*p11*) runs on the server and presents the Cloud datasets to the Web (*p12*). Provide users (*p13*) to use, and finally complete the entire system operations (*p14*).

In summary, by using the WoPeD software tool, the proposed PN model can be qualitatively analyzed. According to the simulation results shown in Fig. 5, the PN model has one

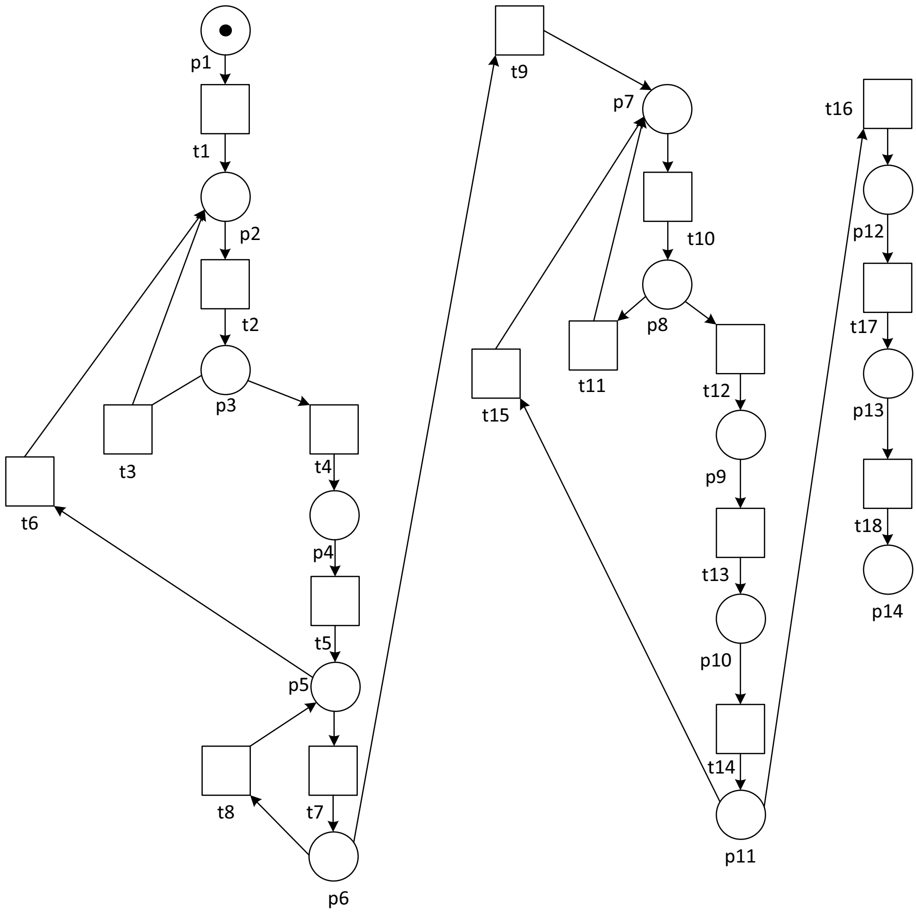

Fig. 3 Petri net model of the proposed monitoring system

Table 3 Interpretation of places

Places	Interpretation	Places	Interpretation
p1	Input token	*p8*	Analysis Data
p2	Hardware	*p9*	Azure SQL Server
p3	The gathering of sensors data	*p10*	The analysis data
p4	Sensors Data	*p11*	ASP.NET Web Form
p5	LRM001(Client)	*p12*	Web
p6	LRM001(Gateway)	*p13*	Users
p7	C# Windows Forms	*p14*	The End

source place, one sink place, strongly connected components, no wrongly marked places, no unbounded places, no dead transitions, and no non-live transitions. In other words, the connection from places to transitions and vice versa does not have any deadlock at all. Since there are no deadlocks, the system is safe. In this manner, the PN model is utilized

Table 4 Interpretation of transitions

Transitions	Interpretation	Transitions	Interpretation
t1	Start system	*t10*	Use Windows Forms
t2	Start hardware tools	*t11*	Return to Windows Forms
t3	Return and check hardware	*t12*	Get data
t4	Send P4	*t13*	Store data to Azure SQL Server
t5	Send data to LRM001(Client)	*t14*	Send data to web application
t6	Return and check hardware	*t15*	Return to web application
t7	Send data to LRM001(Gateway)	*t16*	Use server data
t8	Return and check LRM001(Client)	*t17*	User search web
t9	Send data to windows application	*t18*	End system

to verify and analyze the proposed IoT monitoring system, enhancing its applicability and integrity. Thus, this IoT system is ensured to be totally correct so that it can accelerate the system production [16, 17].

4 Experimental Results

This section presents the hardware information, software design and testing, performance evaluation, and functional comparison.

4.1 Hardware Information

The required hardware information has been described in Sect. 3. Table 5 shows the summary of all hardware components and the datasets collected by the detection stations.

4.2 Software Design and Testing

In this study, three detection stations were set up in the air quality monitoring system. The gateway runs the C# Windows Forms software application (App), which opens the UART communication protocol at both ends. It connects the first end to the REVQ704's own Arduino, and sets COM1 and 9600 Baud, while the second end communicates with the LRM001 of the Mini PCI-E slot, which sets COM4 and 57,600 Baud. The Start button is pressed to start the communication mechanism, which sends the command to complete the LRM001 command configuration. A command was sent to the LRM001, and the RN2903 chip returned the corresponding reply. The command is successful. If there is a command error, the communication will stop.

As shown in Tables 6, 7, and 8, after opening the gateway software App, it receives the values of the sensors from three detection stations. As stated in Sect. 3.4, the header for different locations is identified and the effective hexadecimal value of each string is obtained to get the average value of each item based on the number of datasets received per hour. In addition, every day at 00:00, the 24-h datasets in the cloud database system for the previous day are cleared automatically.

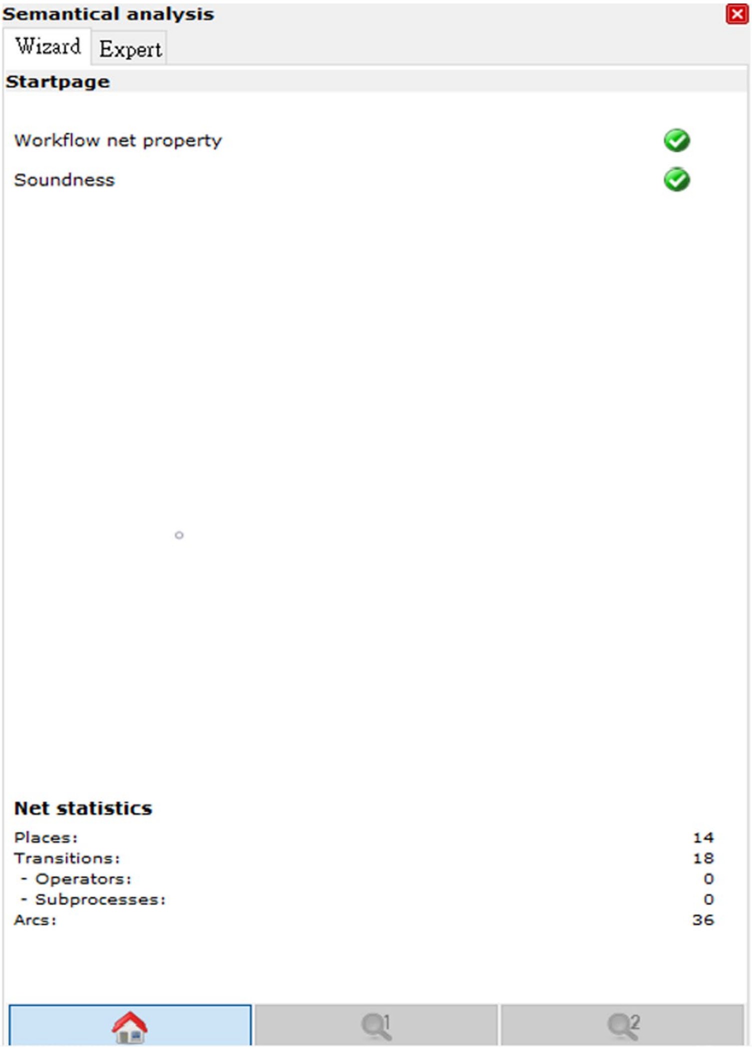

Fig. 4 PN semantical analysis

Apparent temperature (AT) is calculated based on temperature (T), relative humidity (RH), water pressure (e) and wind speed (V) according to formulas (4–1) and (4–2) [31].

$$e = \frac{RH}{100} \times 6.105 \times \exp\left(\frac{17.27 \times T}{237.7 + T}\right) \tag{4-1}$$

$$\mathrm{AT} = \mathrm{T} + 0.33 \times \mathrm{e} - 0.7 \times \mathrm{V} - 4 \tag{4-2}$$

Comfort level (THI) is calculated based on temperature (T) and relative humidity (RH) according to formula (4–3).

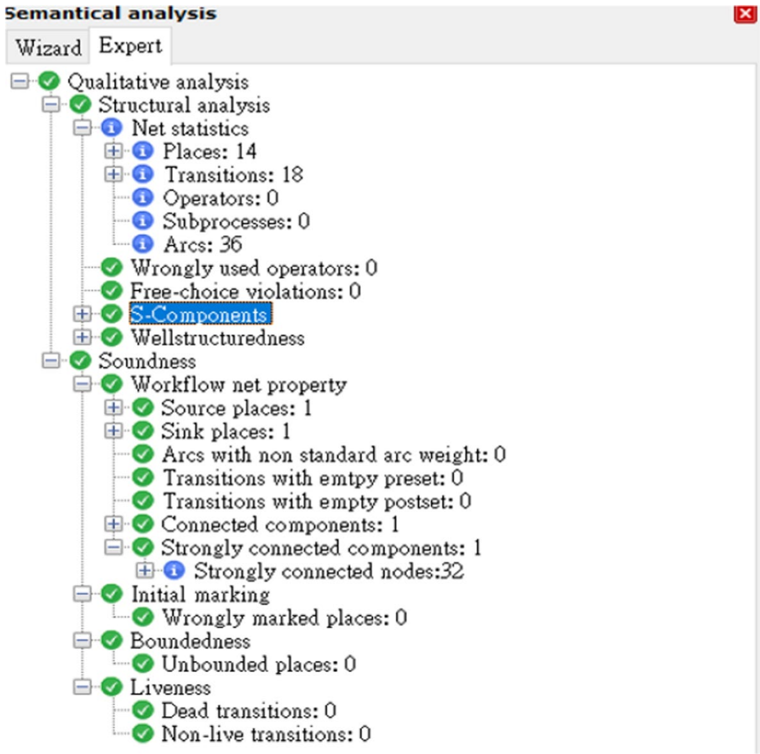

Fig. 5 Simulation results

Table 5 Summary of air detection station information

Location	Hardware	Datasets
Playground (Outdoor)	1. LRM001 2. Arduino Mega 2560 3. PMS5003T 4. JL-FS2 5. GUVA-S12SD 6. Lithium Battery 7. XH-M40111	1. Temperature 2. Humidity 3. Particulate Matter 4. Apparent Temperature 5. Wind Speed 6. Ultraviolet Light
Fifth Dormitory (Indoor)	1. LRM001 2. Arduino Mega 2560 3. PMS5003T 4. MQ-7 5. DSC-CO2-20 6. Lithium Battery 7. XH-M40111	1. Temperature 2. Humidity 3. Particulate Matter 4. Carbon Monoxide 5. Carbon Dioxide
Second Education Building (Indoor)	1. Q7-REV07 2. LRM001 3. PMS5003T 4. MQ-7 5. DSC-CO2-20	1. Temperature 2. Humidity 3. Particulate Matter 4. Carbon Monoxide 5. Carbon Dioxide

Table 6 User interface in App-1

Fifth dormitory			
Temperature:	28	°C	
Humidity:	66.6	%	
THI:	26		Comfortable
PM1.0:	27	μg/m^3	
PM2.5:	45	μg/m^3	unhealthy
PM10:	53	μg/m^3	
CO:	0.1	ppm	
CO_2:	595	ppm	

Table 7 User interface in App -2

Playground			
Temperature:	34.5	°C	
Humidity:	49.5	%	
Wind speed:	1	m/s	
Apparent temperature:	36.6		Sultry
PM1.0:	29	μg/m^3	
PM2.5:	44	μg/m^3	unhealthy
PM10:	56	μg/m^3	
UV:	6		

Table 8 User interface in App-3

Second educational building			
Temperature:	28.9	°C	
Humidity:	67.7	%	
THI:	26		Comfortable
PM1.0:	29	μg/m^3	
PM2.5:	44	μg/m^3	unhealthy
PM10:	56	μg/m^3	
CO:	0.1	ppm	
CO_2:	601	ppm	

$$\mathrm{TH1} = \mathrm{T} - 0.55 \times \frac{1 - \mathrm{GH}}{100} \times (\mathrm{T} - 14) \quad (4\text{-}3)$$

The hourly average value is connected to the Microsoft Azure through the network. The intelligently correlated cloud database service is to store each effectively sensing value in the corresponding table. This system uses SSMS to connect with the Azure SQL database to create a table for each data item, helping the gateway and the server to carry out an access. In addition, users can use this tool to access the cloud database and issue those commands such as add, modify, delete, and search. Figure 8 shows the apparent temperature datasets in the sports field.

After the C# Windows Forms analysis of the gateway is completed, the valid datasets are uploaded to the cloud database system through the network. The C# Web Application of the system is installed in the host at the Department of Electronic Engineering. By adopting the IIS service technology, a terminal server webpage was built. Physical network location can be used to enter the homepage of the campus environmental monitoring network.

Taking the detection station on the playground (i. e. sports field) as an example and clicking the icon, the server receives the commands which lead to the playground information webpage. There are some options at the top for visiting the webpage of other detection station or returning to the homepage of the map. Various sensing information, such as apparent temperature, PM2.5 and ultraviolet light, is all listed in the middle to inform users of the current statuses, as shown in Fig. 6.

Figures 7, 8, and 9 show the values of relative humidity, wind speed, temperature, and apparent temperature [34] detected by the monitoring station on the playground, respectively. By comparing the temperature with the apparent temperature in Fig. 9, the temperature can reach as high as 32 degrees or more during daytime. However, by taking into consideration the humidity and the wind speed, the apparent temperature is higher than the hourly temperature during daytime. Therefore, using the apparent temperature as a reference standard instead of the heat index or the wind chill index is more accurate.

Figure 10 shows the graph of PM1.0, PM2.5, and PM10 measured during daytime. Each detection item can be identified according to the legend provided. With the information bar provided at the top of the webpage, the current air quality analysis results can be obtained. Figure 11 shows the graph of UV measurement, indicating that the UV is strong during daytime, and its value reaches the maximum at noon.

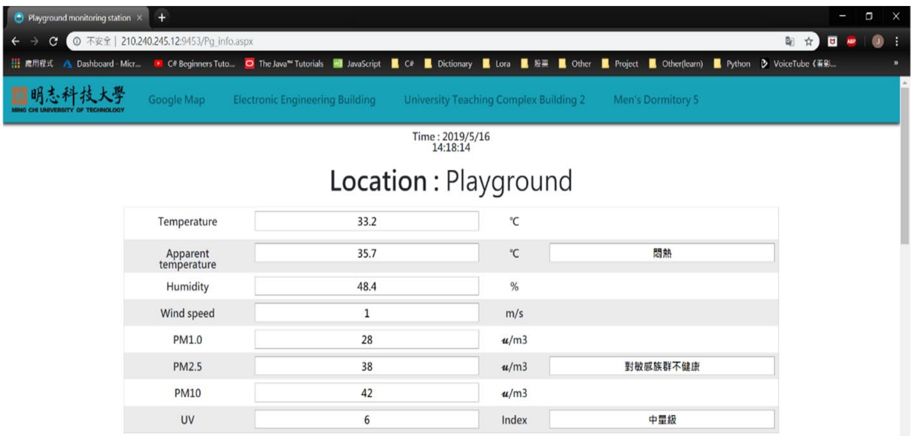

Fig. 6 Detection information on the playground

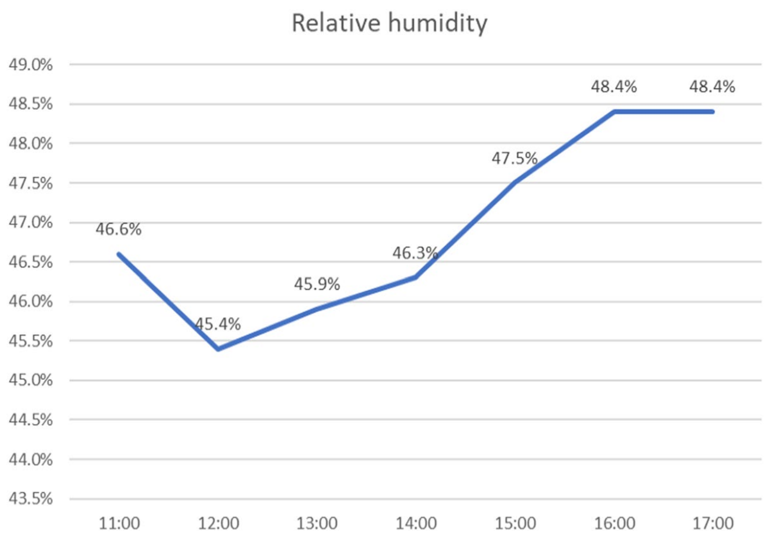

Fig. 7 Relative humidity on the playground

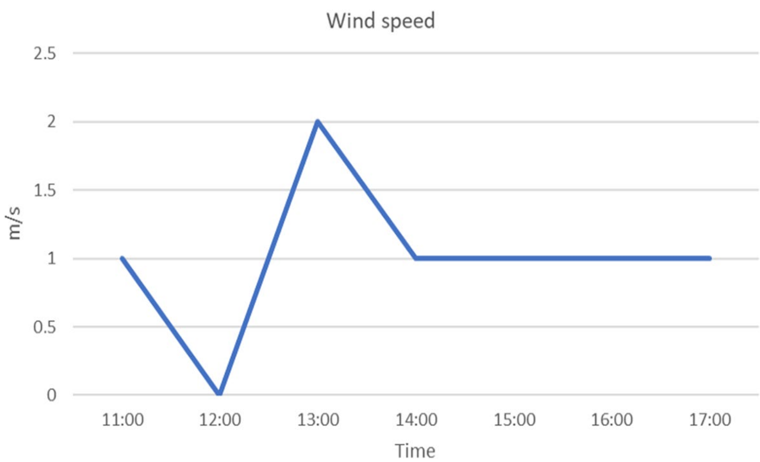

Fig. 8 Wind speed on the playground

4.3 Performance Evaluation

Finally, the success rate of packet transmission in this system is tested. A total of 3000 pieces of dataset are sent from the front-end device to the gateway, with a time interval of 5 s, as shown in Fig. 12. The distances between each station and the gateway are recorded in Table 9. In addition, the LoRa 915 MHz communication transmission results are used to serve as an important basis for the future system development. With LoRa 915 MHz adopted as the communication transmission, despite the presence of several obstacles, the success rate remains at 95% or more.

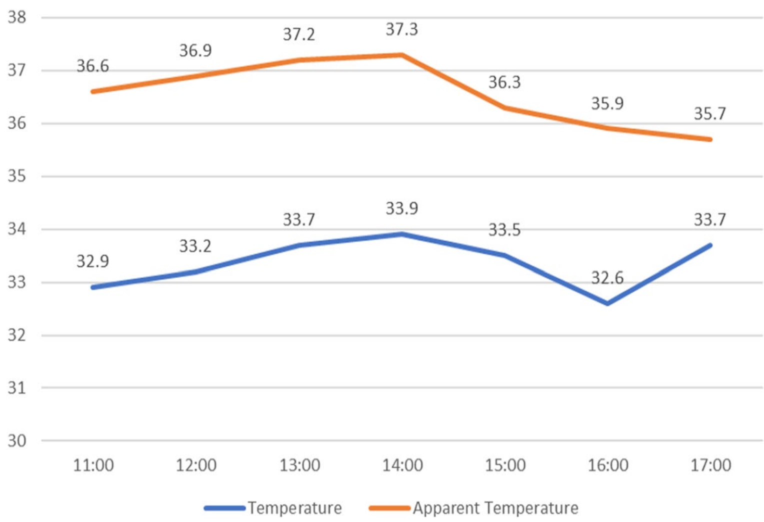

Fig. 9 Temperature and apparent temperature on the playground

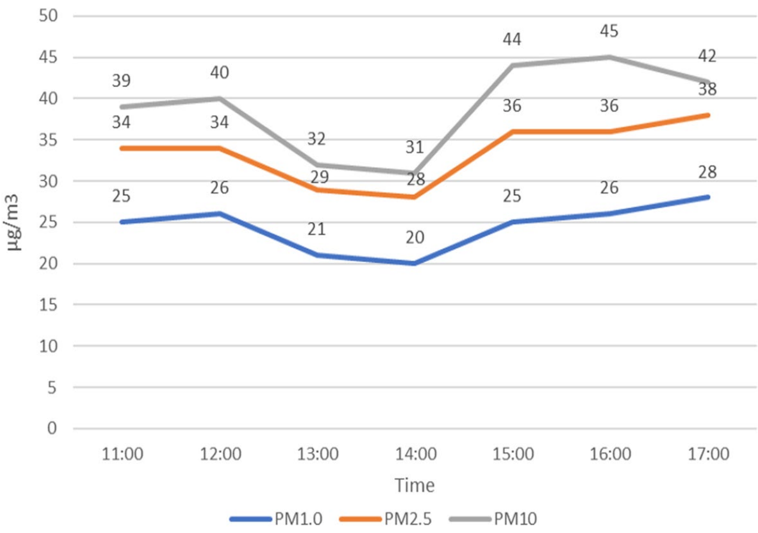

Fig. 10 Particulate matters measurement on the playground

4.4 Functional Comparison

To fully support the claim that our proposed approach is more feasible and acceptable than other existing ones, we have made a functional comparison with each other among different approaches including ours, Po-Ying Wu [9], and Yu-Sheng Lin [10]. The results of functional comparison are shown in Table 10.

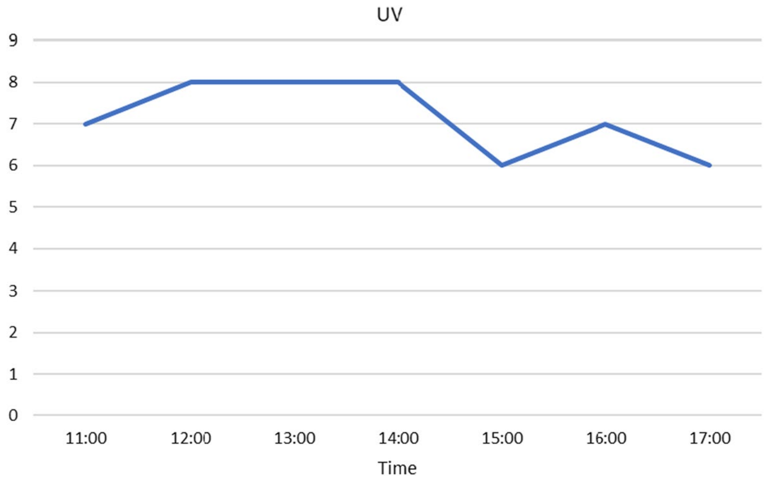

Fig. 11 UV measurement on the playground

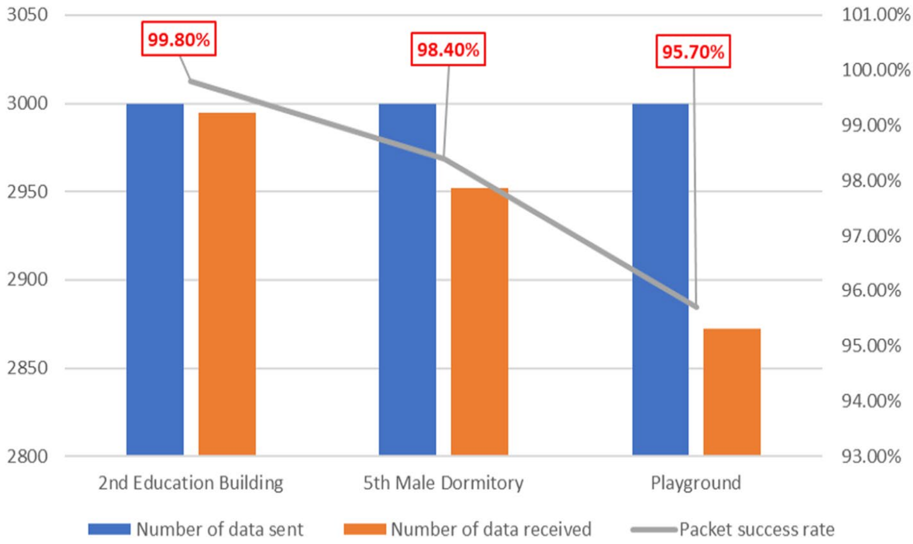

Fig. 12 System packet test

Table 9 System packet transmission success rate

Location	Tested distance	Number of datasets sent	Number of datasets received	Packet success rate (%)
2nd Education Building	0 m	3000	2995	99.8
5th Male Dormitory	470 ± 5 m	3000	2952	98.4
Playground	500 ± 10 m	3000	2872	95.7

Table 10 Results of functional comparison

Index Approach	Average success rate of data transmission (%)	Sensitivity @292bps	Power consumption (W)	Operating temperature	Ethernet isolation	Relative humidity (non-condensing) at 25 °C	System maintenance cost (US$)
Our proposed	97.97	− 140 dBm	2.5	− 40 °C to + 70 °C	1.5 kV RMS	0% to 95%	~ 100
Po-Ying Wu [9]	92.15	− 120 dBm	3.7	− 30 °C to + 60 °C	0.9 kV RMS	0% to 87%	~ 200
Yu-Sheng Lin [10]	91.17	− 110 dBm	4.6	− 20 °C to + 50 °C	0.7 kV RMS	0% to 80%	~ 220

Obviously, our proposed IoT system outperforms other existing systems in terms of average success rate of data transmission, sensitivity, power consumption, operating temperature, Ethernet isolation, relative humidity, and system maintenance cost.

5 Conclusion

The environmental parameters monitoring system on campus has been successfully developed. Three detection stations were set up to monitor different data items according to the needs at each location. A variety of sensors are used to detect the substances that are harmful to people's health, allowing users to easily access the status of various environmental parameters from the university website. At the end, the Petri net software tool was used to analyze and verify the integrity of the proposed IoT system.

The contributions of this study are summarized as follows:

1. The environmental parameters on campus can be viewed from the university website. Users can access the status of environmental parameters at various regions in MCUT, such as temperature, humidity, wind speed, UV light and air quality (e.g. PM1.0, PM2.5, and PM10). Based on the monitored temperature, humidity and wind speed, the apparent temperature can be found out, which is closer to the temperature experienced by users.
2. The LoRa technology with the characteristics of low-power consumption and long-range wireless communication was adopted to replace the traditional wireless communication technology such as Wi-Fi, ZigBee, and BlueTooth.
3. The most suitable protocol among classes *A*, *B*, and *C* is properly determined. By selecting the LoRaWAN in Class *C*, the data latency is minimized. Users always pay attention to whether the datasets are returned. The terminal equipment can reach a balance between downlink latency and battery life.
4. A more stable way of storing datasets was adopted. The Azure cloud database system is used to completely store the datasets, making the maintenance of IoT platform become easy.
5. The experimental datasets are stable so that the wireless communication with LoRa can maintain a packet transmission success rate of more than 95% at the long-range transmission region even with multiple obstacles.

Although this system has been already completed, further improvements are still needed to reach the practical applications. In the future, this project will focus on improving and expanding the system functions. The system will be expanded to six detection stations or more, realizing a star topology of network connection to create a multi-point gateway. In this case, if the gateway encounters a failure, it will not affect the entire system operation. Furthermore, when communicating with the server, it will be distributed anywhere depending on the distance. The gateway with shorter distance is set for returning datasets to the server.

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Data Availability The datasets and code generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest Authors declare that they have no conflicts of interest.

Informed Consent There is no informed consent for this study.

Ethical Approval This article does not contain any studies with human participants and/or animals performed by any of the authors.

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